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Scientific and Technological Experiments on Automatic Space Vehicles and Small Satellites

On-board algorithm for nanosatellite orientation and stabilization system

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Abstract

At the Samara State Aerospace University work on developing of the such nanosatellite is in progress. The main objectives of the nanosatellite are its motion dynamics studying and orientation and stabilization algorithm workout, using the built-in measuring and actuating means which are a part of on-board modules: the three-axis magnetometer placed on the on-board computer; Sun sensors, the angular-rate sensors placed on solar battery panels; magnetic coils. The on-board algorithm for nanosatellite orientation and stabilization system based on the two-vector algorithm of the nanosatellite angular location determination and the nanosatellite angular rate damping algorithm is developing.

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Keywords: Nanosatellite; magnetometer; angular rate sensor; sun sensor; magnetoquer; rejection criteria; orientation determination algorithm; angular motion control algorithm.

Introduction

Now the nanosatellites of CubeSat standard are widely-spread. At the Samara State Aerospace University work on developing of the such nanosatellite is in progress. The main objectives of the nanosatellite are its motion dynamics studying and orientation and stabilization algorithm workout, using the built-in measuring and actuating

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means which are a part of on-board modules: the three-axis magnetometer placed on the on-board computer; Sun sensors, the angular-rate sensors placed on solar battery panels; magnetic coils. The performances of measuring and actuating means are shown in Fig. 1 [1,2]. The limitations imposed by accepted structure of measuring and actuating means, and also the on-board computer performances, form rigid requirements of the orientation and stabilization algorithm computing complexity. As the nanosatellite will be orientated along the vector of orbital motion rate, the spatial orientation determination problem is reduced to a problem of nanosatellite longitudinal axis orientation determination, i.e. determination of pitch angle (ϑ) and yaw angle (ψ), and the problem of controlling is reduced to a problem of dual-channel controlling.

1. The problem statement

In solving the formulated problem the following frames of references are used [3]:

- the orbital frame of reference $OXYZ$ with the origin in the nanosatellite centre of mass: the OZ axis is directed from the pulling centre, the OY axis is coincided with the true anomaly derivative vector (the direction along the bi-normal to the trajectory of the centre of mass), and the OX axis builds the right frame of reference with other two axes.
- the body frame of reference $Oxyz$ with the origin in the nanosatellite centre of mass. The body frame is located as follows: the centrifugal torque of inertia of the nanosatellite is $I_{yz} = 0$, and the Ox axis is the nanosatellite longitudinal axis.

The scheme of solving the formulated problems is shown in Fig. 2.

In fig. 2 the following designations are accepted:

$\begin{bmatrix} H_x & H_y & H_z \end{bmatrix}^T$ - the components of Earth magnetic vector;
$\begin{bmatrix} S_x & S_y & S_z \end{bmatrix}^T$ - the components of current vector from the solar battery panels;
$\begin{bmatrix} \omega_x & \omega_y & \omega_z \end{bmatrix}^T$ - the projections of the nanosatellite momentary angular rate;
$\begin{bmatrix} H_x^* & H_y^* & H_z^* \end{bmatrix}^T, \begin{bmatrix} S_x^* & S_y^* & S_z^* \end{bmatrix}^T$ - the rejected Earth magnetic vector and the rejected current vector from the solar battery panels;
$\Delta\omega_Y, \Delta\omega_Z$ - the change of the values of the projections of the nanosatellite angular rate after the control input.

2. The rejection criteria

2.1 The magnetometric measurements rejection criterion

For the magnetometric measurement rejection it is necessary to calculate the Earth magnetic vector according to the chosen model. After the calculation of the model values of the Earth magnetic vectors the measured Earth magnetic vectors are rejected.

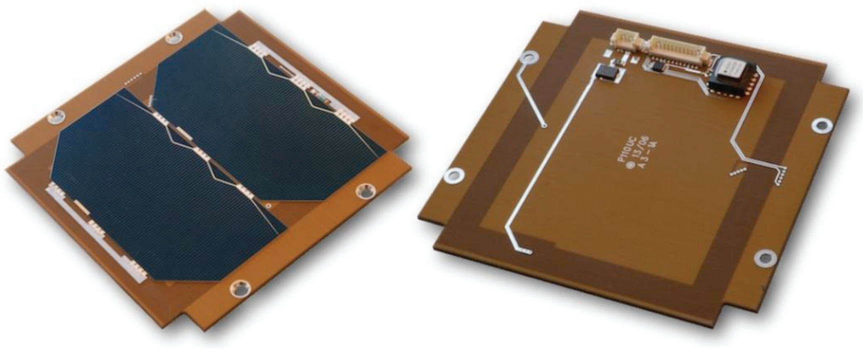
NanoMind A712C

Flight heritage
- Confirmed operational state on spacecraft launched on ESA Vega maiden flight 13/2-2012.
- The technology and design are derived from with heritage in such satellites projects as ESA's SSETI-Express, AAUSAT-II and Baumanetz.

Parameter	Condition	Min	Typ	Max	Unit
Magnetometer					
- Field range		-4		4	gauss
- Measurement time			10		ms
- Resolution			7		mG
- SNR			70		dB

a) – On-board computer

Parameter	Condition	Min	Typ	Max	Unit
Sun Sensor					
- Current	Short current at 1367 W/m^2		930		uA
- Cosine error			1.85	3.5	°
Gyroscope					
- Range				80	°/s
- Sensitivity			0.00458		°/s
- Bias stability			0.016		°/s
- Vcc			5		V
- Current			44		mA
Magnetorquer					
- Area			1.55		m^2
- Resistance		120	135	150	Ohm
- Current	Absolute maximum rating			1	A
- Dipole momentum	Dipole momentum at 3.3V	0.034	0.038	0.043	A m^2



b) – Solar battery panels

Fig. 1 – The performances of measuring and actuating means for the on-board algorithm for nanosatellite orientation and stabilization system

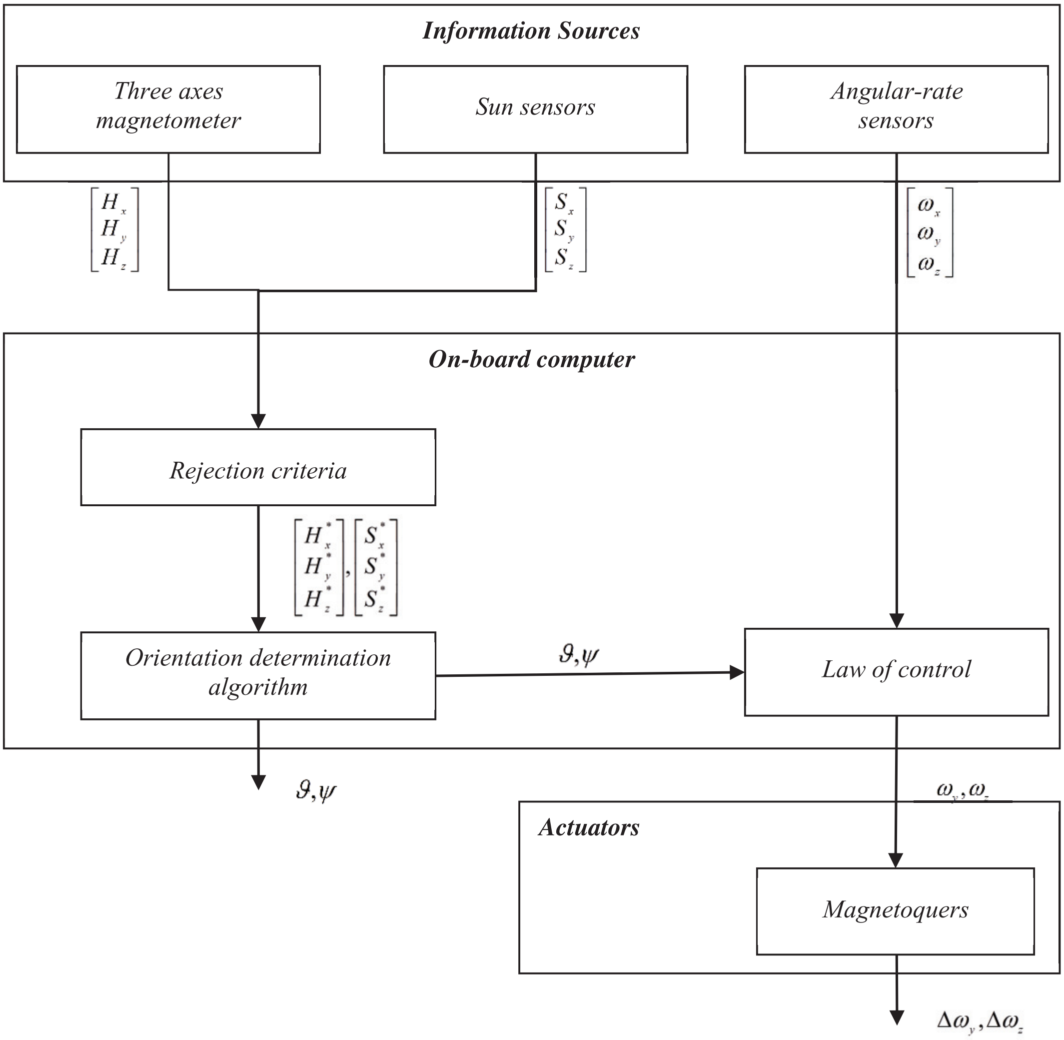


Fig. 2 – The scheme of solving the formulated problems

$$\left|H_{изм} - H_{мод}\right| \le k_1 \delta H,$$
$$\delta H = \left(\delta H_{приб} + \delta H_{мод}\right), \tag{1}$$

where $H_{изм}$ is the measured Earth magnetic vector, $H_{мод}$ is the model value of the Earth magnetic vector, δH is the permissible deviation, k_1 is the safety coefficient ($k_1 > 1$), $\delta H_{приб}$ is the instrumental error, $\delta H_{мод}$ is the error of the Earth magnetic field simulation.

2.2 The current pickup rejection criterion

For the rejection of the current pickup let's use the criterion that is similar to the magnetometric measurements rejection criterion.

$$\left|I_{изм} - I_{мод}\right| \le k_2 \delta I,$$
$$\delta I = \left(\delta I_{приб} + \delta I_{мод}\right), \tag{2}$$

where $I_{изм}$ is the measured current value in solar battery panels, $I_{мод}$ is the model value of the current value in solar battery panels, δI is the permissible deviation, k_2 is the safety coefficient ($k_2 > 1$), $\delta I_{приб}$ is the instrumental error, $\delta I_{мод}$ is the error of the Earth magnetic field simulation.

3. The orientation determination algorithm

As the orientation determination algorithm the two-vector algorithm of the nanosatellite angular location determination is chosen [4]. There are the components of the **S** and **H** vectors in the body and orbital frames of reference at every moment. They are connected by the following relations:

$$\begin{vmatrix} S_x \\ S_y \\ S_z \end{vmatrix} = \mathbf{A} \begin{vmatrix} S_X \\ S_Y \\ S_Z \end{vmatrix}; \quad \begin{vmatrix} H_x \\ H_y \\ H_z \end{vmatrix} = \mathbf{A} \begin{vmatrix} H_X \\ H_Y \\ H_Z \end{vmatrix}. \tag{3}$$

The transfer matrix from orbital to body frame of reference is presented as follows:

$$\mathbf{A}_1 = \begin{bmatrix} \cos\psi\cos\vartheta & -\sin\vartheta & -\sin\psi\cos\vartheta \\ -\sin\gamma\sin\psi + \cos\gamma\cos\psi\sin\vartheta & \cos\gamma\cos\vartheta & -\sin\gamma\cos\psi - \cos\gamma\sin\psi\sin\vartheta \\ \cos\gamma\sin\psi + \sin\gamma\cos\psi\sin\vartheta & \sin\gamma\cos\vartheta & \cos\gamma\cos\psi - \sin\gamma\sin\psi\sin\vartheta \end{bmatrix} \tag{4}$$

The unit axes are

$$\mathrm{p{=}H}; \quad \mathrm{q} = \frac{\mathrm{H{\times}S{\times}H}}{|\mathrm{H{\times}S}|}; \quad \mathrm{r} = \frac{\mathrm{H{\times}S}}{|\mathrm{H{\times}S}|}. \tag{5}$$

The transfer matrices $\mathbf{M_1}$, $\mathbf{M_2}$ from secondary frame of reference *Opqr* to orbital and body frame of reference relatively are

$$\mathrm{M_1^T} = \frac{1}{|\mathrm{H{\times}S}|} \begin{vmatrix} \mathrm{H_x}\,|\mathrm{H{\times}S}| & \mathrm{H_y}\,|\mathrm{H{\times}S}| & \mathrm{H_z}\,|\mathrm{H{\times}S}| \\ \mathrm{S_x\text{-}H_x}\,(\mathrm{H,S}) & \mathrm{S_y\text{-}H_y}\,(\mathrm{H,S}) & \mathrm{S_z\text{-}H_z}\,(\mathrm{H,S}) \\ \mathrm{H_yS_z\text{-}H_zS_y} & \mathrm{H_zS_x\text{-}H_xS_z} & \mathrm{H_xS_y\text{-}H_yS_x} \end{vmatrix};$$
$$\mathrm{M_1^T} = \frac{1}{|\mathrm{H{\times}S}|} \begin{vmatrix} \mathrm{H_X}\,|\mathrm{H{\times}S}| & \mathrm{H_Y}\,|\mathrm{H{\times}S}| & \mathrm{H_Z}\,|\mathrm{H{\times}S}| \\ \mathrm{S_X\text{-}H_X}\,(\mathrm{H,S}) & \mathrm{S_Y\text{-}H_Y}\,(\mathrm{H,S}) & \mathrm{S_Z\text{-}H_Z}\,(\mathrm{H,S}) \\ \mathrm{H_YS_Z\text{-}H_ZS_Y} & \mathrm{H_ZS_X\text{-}H_XS_Z} & \mathrm{H_XS_Y\text{-}H_YS_X} \end{vmatrix}. \tag{6}$$

Using matrices $\mathbf{M_1}$ and $\mathbf{M_2}$, let’s find the transfer matrix from orbital to body frame of reference. The result is

$$\mathrm{A}_2 = \mathrm{M}_1 \mathrm{M}_2^{\mathrm{T}} \tag{7}$$

The angles ϑ, ψ are found using the matrices $\mathbf{A}_1$ and $\mathbf{A}_2$ by well-known trigonometric relations.

4. The nanosatellite angular motion control algorithm

The main problem in the nanosatellite angular motion control algorithm is the angular rate damping after the leading out on the acting orbit and separating from the carrier-rocket.

4.1 The torques acting on the nanosatellite

During the nanosatellite orbital flight in the specified orbit the following disturbing torques have the main influence on the nanosatellite: the gravitational torques and the aerodynamic torque [5].

The gravitational moment appears as a result of the interaction between the nanosatellite and the Earth gravitational field. The projections of the gravitational torque on the axes of the bode frame of reference are determined by formulas [6]:

$$\begin{aligned} M_{x_g} &= \frac{3\mu}{R^3}\left(I_z - I_y\right)c_{23}c_{33}, \\ M_{y_g} &= \frac{3\mu}{R^3}\left(I_x - I_z\right)c_{33}c_{13}, \\ M_{z_g} &= \frac{3\mu}{R^3}\left(I_y - I_x\right)c_{13}c_{23}. \end{aligned} \tag{8}$$

where c_{ij} ($i = 1,2,3$, $j = 1,2,3$) are the elements of the transfer matrix from orbital to body frame of reference; R is the range from the pulling centre to the satellite; μ is the Earth gravitational parameter; I_x, I_y, I_z are the satellite main central torques of inertia.

The aerodynamic torque M_a acting on the nanosatellite is [7]

$$M_a = -m(\alpha_n, \varphi_n) qSl \tag{9}$$

where $m(\alpha_n, \varphi_n) = -C_{xa}(\alpha_n, \varphi_n)\Delta\bar{x}\sin\alpha_n$ is the coefficient of the nanosatellite aerodynamic torque calculated relative to the centre of mass, $C_{xa} = c_0 \tilde{S}(\alpha_n, \varphi_n)$ is the coefficient of the aerodynamic drag, c_0 is the constant coefficient that is dependent on the nature of the interaction between the molecules of the main gas flow and the nanosatellite surface, $\tilde{S}(\alpha_n, \varphi_n)$ is the square of the nanosatellite projection on the plane, which is perpendicular to the direction of the nanosatellite centre of mass rate vector, that is divided by the characteristic square S, $q = \rho V^2 / 2$ is the velocity pressure, V is the value of the flight rate, ρ is the air or gas density, $\vec{e}_v$ is the unit vector, $\Delta\bar{x} = (x_D - x_T)/l$ is the relative stock of the static stability, x_D and x_T are the displacement of the centre of pressure and the centre of mass of the dynamically symmetric nanosatellite about the fixed point O_1.

In projections on the axes of the body frame of reference the aerodynamic torque is written as follows:

$$\begin{aligned} M_{xa} &= 0 \\ M_{ya} &= M_a \cos\varphi_n , \\ M_{za} &= -M_a \sin\varphi \end{aligned} \tag{10}$$

4.2 The nanosatellite motion equations

Let's write the equation system of the nanosatellite motion in general [15] in body frame of reference

$$\frac{d\vec{K}}{dt} + \vec{\omega} \times \vec{K}_0 = \vec{M}_0 , \tag{11}$$

where $\vec{\omega}$ is the absolute angular rate, $\vec{K}_0 = I\vec{\omega}$ is the vector of the kinetic torque, I is the tensor of inertia, $\vec{M}_0$ is the main torque of the outside forces.

It is supposed that the axes of the body frame of reference are the nanosatellite main central axes of inertia for point O. Then the vector equation (11) in projections on the given axes is written as follows:

$$\begin{aligned} I_x\dot{\omega}_x + (I_z - I_y)\omega_y\omega_z = M_x, \\ I_y\dot{\omega}_y + (I_x - I_z)\omega_z\omega_x = M_y, \\ I_z\dot{\omega}_z + (I_y - I_x)\omega_x\omega_y = M_z, \end{aligned} \tag{12}$$

where M_x, M_y, M_z are the projections of the main torque of the outside forces on the axes of the body frame of reference; ω_x, ω_y,ω_z are the projections of the angular rate $\vec{\omega}$ on the axes of the body frame of reference.

Taking into account that the orbit is circular let's add three kinematic equation to the dynamic equations. The kinematic equation provide the connection between the first time derivatives of the Euler angles α_n, φ_n and γ_a (the precession angle – the angle of the high speed roll γ_a, the nutation angle – the spatial angle of attack α_n, the angle of the own rotation - the angle of the aerodynamic roll φ_n) and the projections of the angular rate on the axes of the body frame of reference ω_x, ω_y and ω_z:

$$\begin{aligned} \omega_x &= \dot{\gamma}_a \cos\alpha_n + \dot{\varphi}_n, \\ \omega_y &= \dot{\gamma}_a \sin\varphi_n \sin\alpha_n + \dot{\alpha}_n \cos\varphi_n, \\ \omega_z &= \dot{\gamma}_a \cos\varphi_n \sin\alpha_n - \dot{\alpha}_n \sin\varphi_n. \end{aligned} \tag{13}$$

4.3 The nanosatellite angular rate damping algorithm

Let's describe the nanosatellite angular rate damping algorithm [8] for that the information about the sign of the derivative of the components of the Earth magnetic vector is required. The dipole magnetic torque $\mathbf{L}$ is formed according the law

$$\mathbf{L} = -\mathbf{L}_{\max}\,\mathrm{sign}(\dot{\mathbf{H}}) \tag{14}$$

Here $\mathrm{sign}(\dot{\mathbf{H}})$ is the sign of the derivative of the components of the Earth magnetic vector.

Algorithm operation logic contains the follows: reasoning from the information about the rotation of the Earth magnetic vector in body frame of reference the control torque is formed. This control torque rotates the satellite in opposite direction.

The idea of the supposed control law is in imitation of the damper acting that is built on the use in nanosatellite the element from the low-coercitivity material [9]. The magnetic reversal of the low-coercitivity element causes the dispersion of the satellite motion energy about the centre of mass. The supposed control law imitates the magnetic torque of the ideal hysteresis rod with the rectangular hysteresis loop. The given algorithm switch on automatically while switching on system power supply, and also while the magnitude of the angular rate is more than the threshold value of 0,5 °/s according to the mission control centre decision.

Conclusion

The anticipated accuracy of solving the problems: in the nanosatellite orientation determination problem it will be 10°; in the nanosatellite orientation control problem it will be ± 5°.

Acknowledgements

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